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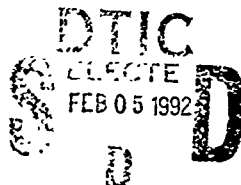
FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS
Technical Progress Report

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I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene 80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200 + Hf airfoils. The DS process produces a $\langle 001 \rangle$ crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils¹.

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the $\langle 001 \rangle$ crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials

¹ Gell, M., D. N. Duhal, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blade," *Superalloys 1980*, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.



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is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in $\langle 001 \rangle$ type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstructural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the $\langle 001 \rangle$ crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple $\{111\}$ planes or under certain circumstances as $\{001\}$ cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along $\{111\}$ shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along $\{111\}$ planes occurs, or may transition to subcritical crystallographic propagation. At 982C, propagation is almost entirely noncrystallographic, similar to transgranular propagation in a polycrystal.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage states. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is organized into four tasks, which are described in the following paragraphs.

II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

We have previously concentrated on stress intensity and temperature dependant transitions in fatigue crack growth modes. During this reporting period our efforts have focussed on the micromechanics of fatigue crack initiation.

To characterize the incubation phase of the fatigue process it is necessary to consider the nature of the various sources of fatigue crack initiation. Fatigue cracks typically initiate at defects. Defects can be thought of as falling into two basic types, those of intrinsic material quality (IMQ) and those stemming from deviant material. IMQ defects are a normal feature of an alloy and are included in material capability curves and empirically based life prediction systems. There

are established tolerance limits on these. Rejectable defects are defects stemming from some deviation in material quality that exceeds specified limits. They are not included in alloy capability curves. Within the scope of this program it is practical to make some observations regarding such details as threshold size for initiation, size probability density and the micromechanics that characterize activation of a particular defect species. A micromechanical assessment of incubation time could allow the prediction of IMQ defect driven initiation life based on the energy imparted to the microstructure during cyclic loading. Identification of the micromechanisms of initiation will be an important part of this effort.

Recent SEM review of PWA1484 fractures produced at 800F, shows secondary crack formation at the interface between the eutectic phase and the bulk microstructure. This provides an indication that the eutectic phase can become a fatigue crack initiator at this temperature. Thin film TEM analysis has demonstrated heavy dislocation concentrations at the eutectic/bulk interface in PWA 1480. Cyclic straining eventually results in some critical dislocation density being reached at this interface. Historical 600F PWA 1480 fractures have been examined specifically for additional evidence of this phenomena. These fractures show an extreme case of this mechanism where the phase has experienced decohesion from the microstructure bulk, ie. pulled out. The interface between the defect and the surrounding bulk microstructure will be studied further in an attempt to obtain the critical dislocation densities associated with defect activation.

IV. Current Problems

No technical problems have been encountered during the reporting period.

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